THE

PHYSICAL SOCIETY

OF

LONDON.

PROCEEDINGS.

VOLUME XXXI.—PART II.

FEBRUARY 15, 1919.

Price to Non-Fellows, **4s.** *net, post free* **4/3.**

Annual Subscription, **20/-** *post free, payable in advance,*

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m December to August.

The price of this publication has been increased 50% as from Dec. 1920.

ONDON:
FLEETWAY PRESS, LTD.,
1, 2 AND 3, SALISBURY COURT, FLEET STREET.

1919.

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1918-19.

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DISCUSSION ON

"THE CASE FOR A RING ELECTRON."

A Meeting of the Society was held on Friday, October 25, 1918, at the Imperial College of Science, South Kensington, when a discussion took place on "The Case for a Ring Electron."

The chair was taken by the President, Prof. C. H. Lees, F.R.S., who called upon Dr. H. S. Allen to open the discussion.

II. *The Case for a Ring Electron. By* DR. H. S. ALLEN.

FOR many purposes it is sufficiently accurate to regard the unit of negative electricity as a point charge, but for a more exact determination of its properties it is necessary to assign some definite shape to the distribution of electricity constituting the electron. Thus, the shape is often assumed to be that of a sphere or spheroid. Although the spheroidal form possesses advantages from the standpoint of mathematical analysis, there are many reasons why it is preferable to assume that the electron is in the form of a current circuit which can produce magnetic effects. Then the electron, in addition to exerting electrostatic forces, behaves like a small magnet. In its simplest form the magnetic electron may be looked upon as a circular anchor ring of negative electricity which rotates about its axis with a velocity which is certainly large, and is perhaps comparable with that of light. Parson* has suggested that the name *magneton* should be applied to this electron; but, as this term has already been employed in a somewhat different sense, I prefer to speak of the ring electron.

With reference to the corpuscular theory of light, Sir Isaac Newton wrote: "I shall not assume this or any other hypothesis, not thinking it necessary . . . yet, while I am describing this to avoid circumlocution and to represent it more conveniently, I shall speak of it as if I assumed it and proposed it to be believed." In collecting the arguments in favour of the ring electron I do not wish it to be understood that I am in agreement with them all or with the views of all those who have supported this hypothesis. Some of the arguments have been well stated in Parson's Paper on a magneton theory of the structure of the atom.

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* Parson, "Smithsonian Misc. Coll.," Vol. LXV., No. 11, 1915.

PART I.—THE ARGUMENTS FOR A RING ELECTRON.

1. *Loss of Energy by Radiation.*—The most important difficulty in connection with the classical electron is that of the radiation which must take place, according to the laws of electrodynamics, when the electron (or a number of electrons) is circulating in an orbit. This difficulty, though perfectly well known, is usually ignored altogether in the discussion of atomic theories. When the number of electrons in the orbit is increased the loss of energy is greatly diminished, and the difficulty may be met to a certain extent by postulating rings containing many corpuscles. We now know, however, that in the case of the lighter atoms—hydrogen, helium, lithium—the number of electrons is small; in fact, it appears certain that Moseley's atomic numbers, $H=1$, $He=2$, $Li=3$ . . . . must be accepted as representing the number of electrons in the atom. The only way left of meeting the difficulty for the classical electron is to postulate such a "binding" of the electron to the nucleus as precludes radiation in the stationary state of the system (Bohr). This is, of course, purely hypothetical, and it is certainly simpler to do away with the difficulty altogether by assuming the rotation of an annular change. Radiation will then occur only in the case of disturbances or irregularities in the annular motion.

2. *Diamagnetism.*—The second objection to the prevailing theory arises in connection with the explanation of diamagnetic atoms—and most substances are diamagnetic. In order to account for a zero resultant magnetic moment, the independent orbits must be considered to have their axes uniformly distributed in three dimensions. Interference between separate rings of this sort would result in an altogether chaotic motion in the atom. Whilst such chaotic motion would be consistent with diamagnetism, it would invalidate all those considerations which presuppose the existence of definite periods of vibration in the atom. The question is discussed at some length in Parson's Paper. The substitution of the ring electron for Langevin's electron in orbital motion removes the fundamental difficulties of his theory, but leaves the

superstructure almost intact. That this substitution can be made will be made clear by a short quotation from the conclusion of his Paper :—

" . . . and we can form a simple and exact picture of all the facts of magnetism and of diamagnetism by imagining the individual currents produced by the electrons to be indeformable but movable circuits of no resistance and very great self-induction, to which all the ordinary laws of induction are applicable."

3. *Paramagnetism.*—In the older theory there are certain outstanding difficulties in connection with the explanation of paramagnetic properties. No satisfactory explanation has yet been given as to how the orbits become tilted under the influence of an external magnetic field. Although it may not be easy to develop a complete mathematical treatment of the behaviour of the ring electron in a magnetic field, it would certainly seem easier to understand the tilting of such a system than that of a single particle moving in a closed orbit.

By means of X-ray photographs showing the Laue diffraction pattern for crystals of magnetite, hematite and pyrrhotite in the magnetised and unmagnetised state, K. T. Compton and Trousdale* came to the conclusion that the atoms do not leave their positions of equilibrium during magnetisation. These results may be regarded as consistent with any form of the electron theory of magnetism, but the hypothesis of ring electrons seems to afford a particularly clear and straightforward explanation of the phenomenon.

A further step in the analysis was taken by A. H. Compton and O. Rognley†, who examined the intensity of the beam of X-rays reflected from a crystal face. In no case was any change observed in the intensity of the reflected beam when the crystal was magnetised or demagnetised, though the method was sufficiently sensitive to detect a variation in the intensity of less than 1 per cent. Since the intensity depends upon the arrangement of the electrons in the atoms which make up the crystal the authors conclude that it is neither a group of atoms, such as the chemical molecule, nor the atom itself which is the elementary magnet. We must look to the atomic nucleus, or to the electron for the ultimate magnetic particle.

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* K. T. Compton and Trousdale, "Phys Rev.," Vol. V., p. 315, 1915.

† A. H. Compton and O. Rognley, "Phys. Rev.," Vol. XI., p. 132, 1918.

The existence of a zero point energy of rotation is supported by the magnetic susceptibility of paramagnetic substances. According to Oosterhuis* most of the deviations from Curie's law found at low temperatures may be explained quantitatively on this assumption. This view has been supported by Keesom.† It receives a natural explanation if the ring electron be accepted, for the electron would retain its magnetic properties at low temperatures.

The existence of a mechanical effect accompanying magnetisation was foretold by Richardson‡ in 1908. Assuming that the resultant magnetic fields which the atoms of magnetic (as opposed to diamagnetic) substances possess, arise from the motion of their constituent electrons in closed orbits, there must be a moment of momentum per unit volume proportional to the intensity of magnetisation. Einstein and De Haas § succeeded in observing the effect predicted by Richardson, and obtained a factor of proportionality corresponding to that which would be due to negative electrons. Experiments at Princeton by Stewart || led to a value only one-half that obtained previously. The magnitude of this momentum can be accounted for if positive, as well as negative, charges are moving within the atom, but in opposite directions. A similar result was obtained in the work of S. J. Barnett,¶ who showed that a rotating cylinder of iron becomes magnetised. This may be regarded as the converse of the Richardson effect. The relation of these phenomena to the properties of the ring electron has been discussed by Webster.**

4. *The Asymmetry of Certain Types of Radiation.*—In order to explain the asymmetry of scattered X-radiation A. H. Compton †† has examined theoretically the scattering to be expected when the electron is in the form of a spherical shell, each part of which can scatter independently and may be capable of rotational motion. He found that it was then possible to explain not only the asymmetry of the scattered rays, but also the diminution of scattering with decrease of wave length. Since the mass of an electron cannot be

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* Oosterhuis, "Phys. Zeitschr.," Vol. XIV., p. 862, 1913.

† "Konink. Akad. Amsterdam," Vol. XVI., pp. 454 and 468, 1913.

‡ Richardson, "Phys. Rev.," Vol. XXVI., p. 248, 1908.

§ Einstein and De Haas, "Deutsch. Phys. Gesell.," Vol. XVII., p. 152, 1915.

|| Stewart, "Phys. Rev.," Vol. XI., p. 100, 1918.

¶ S. J. Barnett, "Phys. Rev.," Vol. VI., p. 239, 1915.

** Webster, "Phys. Rev.," Vol. IX., p. 484, 1917.

†† Compton, "Journ." Wash. Acad. Sci., January 4, 1918.

accounted for on the basis of a uniform distribution of electricity over the surface of a sphere, Compton suggested that the true shape of the electron may be that of a ring. His estimate of the radius is $2 \cdot 3 \times 10^{-10}$ cm., but reasons have been given for supposing that this estimate must be reduced to about one-tenth of the value stated.*

The same kind of asymmetry occurs in the case of corpuscular radiation excited when X-rays fall on a thin plate of any material. E. A. Owen† has recently carried out experiments which show that no difference can be detected between the ratio of emergent to incident corpuscular radiation when the screen from which the corpuscles are ejected, is changed from the crystalline to the amorphous state. This result renders doubtful the explanation of asymmetry put forward by H. A. Wilson, who attributed it to the difference between the behaviour of crystalline and amorphous material, and suggests that an explanation of a more fundamental character is necessary to account for this phenomenon. This view is supported by the fact that the ratio of emergent to incident corpuscular radiation is approximately the same for the two salts investigated and for the metals, gold and silver. It would appear that the asymmetry must be due to some property of the electron itself and not of the atom from which the electron is liberated.

5. *Absorption of X-rays by Magnetic Substances.*—It has been observed by A. H. Forman‡ that iron has a slightly greater absorption coefficient for X-rays when magnetised parallel to the transmitted beam than when unmagnetised.§ This may be attributed to the fact that when the axis of the ring electron is parallel with the incident X-rays the energy scattered by the electron is a maximum. (A. H. Compton.)

6. *Ionisation of Gases by X-rays.*—It has long been known that the ionisation produced in a gas by Röntgen radiation or ultra-violet light is remarkably small; when the ionisation is strong the ratio of the free ions to the number of gas molecules is less than $1 : 10^{12}$. This may be explained by some form of the unitary theory of light, but an alternative explanation

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* "Nature," Vol. C., p. 510, 1918.

† E. A. Owen, "Proc." Phys. Soc., Vol. XXX., p. 133, 1918.

‡ A. H. Forman, "Phys. Rev.," Vol. VII., p. 119, 1916.

§ In Faraday's note-book is found the suggestive query: "Does this [magnetic] force tend to make iron and oxide of iron transparent?"

may be suggested to the effect that there may be only one plane in which the electrons can absorb sufficient energy from the Röntgen ray for ionisation.*

These ideas may have some bearing upon the work of Righi† on the ionisation of gases by X-rays in a magnetic field. Experiments carried out under very varied conditions led to the conclusion that the magnetic field tends to favour ionisation of a gas by diminishing the energy required. Thus an ion or an electron in motion can ionise a gaseous atom on collision, when a magnetic field exists, although the kinetic energy of the electron does not reach the minimum value that is necessary in the absence of the magnetic field. This effect is termed "magneto-ionisation."

7. *Thermo-Electric Effects.*—Grondahl‡ claims to have obtained experimental evidence for the existence of an electron endowed with a magnetic moment. Such an electron would be affected by a non-uniform magnetic field. A conductor placed in such a field would therefore gain a negative potential in that part which lies in the stronger portion of the field. A magnetic field should produce an effect on the thermo-electric force of magnetic substances. This effect was examined in the case of a copper iron couple, the iron member of which was a short wire which could be placed in a magnetising coil. Theory predicts an increase in the thermal E.M.F., and this was actually observed and found to be of the order of magnitude to be expected.

8. *The Radiation Formula of Planck.*—A method of deducing Planck's radiation formula by making certain assumptions as to the internal mechanism of Parson's "magneton" has been given by Webster.§ Energy is stored in the rotating ring in a non-radiating form. "If the electricity is movable on the ring in any other way than as a rigid mass, the alternating external force of a light wave will induce oscillations on it capable of absorption and radiation of energy. These induced oscillations were shown to give an explanation of refraction, diffraction and allied phenomena almost exactly like that of the classical

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* Cf. A. H. Forman, *loc. cit.*

† Righi, "R. Accad. Sci.," Bologna, Vol. IV., p. 1, 1916-1917; Vol. V., p. 3, 1917-1918.

‡ Grondahl, "Phys. Rev.," Vol. X., p. 586, 1917.

§ Webster, Amer. Acad. "Proc.," Vol. L., p. 131, 1915; "Phys. Rev.," Vol. VIII., p. 66, 1916.

electron theory. At the same time the internal mechanism assumed above for transferring energy between the oscillations and the circulation can be supposed to damp the induced oscillations, transferring their energy to the rotation, until the energy accumulated above the initial value reaches some definite multiple of the quantum. At such a point it is assumed that the process may be reversed, starting a large oscillation, which will be maintained constant at the expense of the circulation, until the excess energy is all radiated away. The probability, η, that such an oscillation will start when the stored energy reaches a given multiple of $h\nu$ is given by Planck's condition $(1-\eta)/\eta = pI$, where I is the mean square of the electric field per unit frequency interval, and p is determined so as to give the Jeans-Rayleigh law at low frequencies. The entropy of the system is then found by Planck's equation $S = k \log W$, where the microscopic state of a system is determined by the total accumulated energy of each oscillator. The derivation of Planck's law in this theory is therefore almost exactly like his."

Attention may again be drawn to the significance of Planck's constant, h, which may be regarded as a quantum of action. The view, first suggested by Nicholson, that h represents an angular momentum is simpler and easier to realise. McLaren identified the natural unit of angular momentum with the angular momentum of the magneton, and it has been pointed out several times that this implies proportionality to the magnetic moment of the magneton. Thus the ring electron serves to give an intelligible meaning for this " universal " constant, and at the same time suggests the possibility of a relation between h and e. Such a relation has in fact been put forward by Lewis and Adams in the form

$$15c^3h^3 = 8\pi^5(4\pi e)^6,$$

an equation based on a certain assumption as to the form of the constant in Stefan's law of radiation.

9. *Series of Lines in Spectra.*—The theory of line spectra proposed by Bohr has met with a considerable amount of success at least in connection with the hydrogen spectrum, and the developments made by Sommerfeld and others have afforded an explanation of the fine-structure of the hydrogen lines. It may prove possible to restate Bohr's theory and, whilst retaining its essential features, modify it so as to apply

it to the case of the ring electron. Thus it might be suggested that the " stationary state " of the electron in its orbit corresponds to a particular value of the radius of the annular electron, the change from one stationary state to another corresponding to a definite change in the radius. It would, of course, be necessary to introduce some hypothesis to fix the size of the ring, just as it is necessary to postulate the stationary state in Bohr's theory. In the last-named theory no detailed assumptions are made as to the mechanism of transition between two stationary states or as to the mode of emission of radiation. In the case of the ring electron radiation might arise from pulsations of the ring in its passage from one stationary condition to another. In this connection it is interesting to recall the views of Sutherland * with regard to the origin of lines in spectral series. He came to the conclusion that the series must arise from kinematical considerations and explained them by considering the nodal sub-divisions of a circle.

It may be well again to draw attention to the fact that, as shown by Nicholson, coplanar rings of electrons are not possible when electrostatic forces alone are taken into consideration. Provided the electrons are in one plane they must form a single ring. The assumption of rings of electrons is no longer required if both electron and core are endowed with magnetic properties, as the electrons may then be supposed to take up positions of statical equilibrium with reference to the core—a condition of affairs which is in harmony with the facts of chemical combination and crystalline formation.

10. *The Zeeman Effect.*—In the simple theoretical explanation of the Zeeman effect first given by Lorentz, the motions of the electrons in a luminous source are analysed into three components, a vibration parallel to the lines of magnetic force and two circular motions, clockwise or anti-clockwise, in planes normal to the lines of force. The vibrations are assumed to take place under the influence of " elastic " forces, attracting the electrons towards a position of equilibrium. Although explanations of the magnetic effect have been given by the combination of the quantum hypothesis with Bohr's atomic model, Debye has emphasised the fact that with these assumptions there is no place left for the quasi-elastic oscillating electrons which have been used in

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* Sutherland, " Phil. Mag.," Vol. II., p. 245, 1901.

all theories for the explanation of the Zeeman effect from Lorentz to Voigt. Mention should be made of the theory of Ritz in which the electron moves in an orbit in a plane perpendicular to the axis of a magnet formed by the addition of a number of elementary magnets, which are the same for all substances.

If radiation is due to pulsations in a ring electron, it would seem that the Zeeman effect should follow from reasoning similar to that first employed by Lorentz.

For consider a " pulse " in the form of a small " hump " travelling round the ring. This may be regarded as equivalent to a particle of mass km and charge ke (where k is a fraction of the total mass or total charge) travelling in a circular path under the influence of elastic forces. A magnetic field would produce a change of period (positive or negative) as in the theory of Lorentz proportional to ke/km, that is to e/m.

The complex resolutions sometimes observed under the influence of the magnetic field may possibly be explained as arising from more complicated pulsations of the ring. Runge has made known a rule which states that the complicated magnetic resolutions are in simple relation with the normal value of e/m. Ritz has endeavoured to explain the magnetic resolutions by a kind of precessional movement of the system round the lines of force as axis. This theory and those put forward by Lorentz and Voigt may be found discussed in the last chapter of Zeeman's " Researches in Magneto-Optics." " Voigt has abandoned the supposition of magnetically isotropic, arbitrarily orientated particles, and modified Lorentz's system of equations. He supposes that the radiating particles are orientated under the action of the field." The results obtained on this assumption are competent to explain all the resolutions observed. The hypothesis of the ring electron appears to furnish exactly what is required for a basis of this theory. In particular it explains the difficulty as to the absence of an undisplaced line in light emitted perpendicular to the field, for the electron would set at right angles to the magnetic field and there would be no motion of parts of the ring parallel to the lines of magnetic force.

11. *Solar Electron Streams.*—The view that magnetic storms and the auroræ are due to ionisation of the outer regions of the atmosphere by streams of electrons or ions

projected from the sun is now commonly received. Schuster [*] has drawn attention to the fact that the electrostatic forces due to a cloud of charged particles would tend to scatter the particles to a considerable extent. If, however, the electron possesses the properties of a small magnet, a little consideration will show that the magnetic forces would tend to diminish the scattering effect. This may make it easier to understand the sudden commencement of magnetic storms, which would be difficult to explain if the electron stream is widely scattered before reaching the earth. Even if the effect referred to is small, it may not be negligible in the case of a crowd of electrons moving in a magnetic field.

12. *Chemical Considerations.*—Serious difficulties are met with when an attempt is made to apply the conception of the electron at present in vogue to problems of chemical constitution and stereochemistry. Any theory in which the electrons are in rapid orbital motion is difficult to reconcile with the stereochemical evidence for a definite spatial arrangement of the groups of atoms attached to a carbon atom, especially as the rings of electrons must usually all rotate about the same axis. These difficulties have been discussed at length by Parson. What seems to be required is the existence of chemical " linkages " or " bonds " having definite relations in space with reference to the atom, and yet admitting of a certain mobility. This involves the presence of valence electrons which are at rest, or vibrating within narrow limits, near the surface of the atom. Stark has developed a theory on these lines, taking into consideration only electrostatic forces. Nicholson [†] has discussed the stability of such systems and has shown that Stark's conclusions do not survive a quantitative treatment. It appears to be impossible for two atoms in a molecule to be linked by a single electron, or by two electrons, which attract both atoms.

The introduction of a magnetic electron, producing both an electric and a magnetic field, furnishes a means of avoiding these difficulties, so that it becomes possible to retain stationary electrons and at the same time the orbital motion which is required to explain radiation and magnetism. It is perhaps well to emphasise the fact that this theory includes *both electrostatic and magnetic* attractions and repulsions. It is probable that the electrostatic forces play the most important part in the formation of chemical compounds, especially in those of "polar" type, whilst the magnetic forces may be regarded as permitting a stable arrangement of stationary atoms and electrons.

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[*] Schuster, " Proc." Roy. Soc., Vol. LXXXV., p. 44, 1911.

[†] " Proc." Phys. Soc., Vol. XXX., p. 65, 1918.

The presence of eight groups in the periodic table indicates that for the majority of elements eight electrons are required to form a stable system. This is brought out in the arrangement of the table which I published recently in the "Transactions" of the Chemical Society.* In place of Newland's "law of octaves" we have what may be termed the "rule of eight." This rule is brought into prominence when atomic numbers are inserted in the periodic classification.

The same rule is obeyed in the case of chemical compounds, as is shown most clearly by the "molecular numbers" which I have introduced. The molecular number signifies the sum of the positive charges carried by the atomic nuclei contained in the molecule. Both Parson and Lewis † have emphasised the fact that the groupings required by chemistry are, in general, of two sorts, one a pair of electrons closely associated, and the other a very compact group of eight. These are exactly the groupings that might be expected from magnetic doublets, for Parson has shown that the group of eight forms an extremely stable system of low magnetic energy.

13. *Cohesion.*—That the cohesion of a solid arises from the action of electric or electro-magnetic forces may be inferred from optical experiments. The Lorentz-Fitzgerald hypothesis explains the negative result of the Michelson-Morley experiment by a contraction of the material framework of the apparatus in the direction of its motion through the æther. Such a contraction, which is essential according to the principle of relativity, may be predicted from the standpoint of electromagnetic theory. There is, therefore, a strong presumption that the forces of cohesion between the particles, which give a solid its rigidity are either electric or magnetic forces.

All chemical forces also are probably of electromagnetic origin, and in the light of our present knowledge it does not seem possible or advisable to distinguish sharply between chemical and physical forces. Indeed, Langmuir,‡ in an interesting Paper on the constitution and fundamental properties of solids and liquids, concludes that both solids and liquids consist of atoms held together entirely by *chemical forces.* The phraseology may serve a useful purpose if it serve to emphasise the essential identity between the forces imparting rigidity to a crystal and those conferring stability on the molecule of an organic compound.

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* H. S. Allen, Chem. Soc. "Trans.," Vol. CXIII., p. 389, 1918.

† Lewis, "Journ." Am. Chem. Soc., Vol. XXXVIII., p. 762, 1916.

‡ Langmuir, "Journ." Amer. Chem. Soc., Vol. XXXVIII., p. 2221, 1916.

In this connection it is of interest to recall the work of Lewis * on the relation between the internal pressure or cohesion P in the equation

$$(p+P)(v-b)=RT,$$

and the dielectric capacity and magnetic permeability of a liquid. He has shown that the Obach Walden relation regarding the proportionality between the internal pressure and the dielectric constant follows from the hypothesis that molecular attraction is electromagnetic, not electrostatic in nature.

PART II.—THE PROPERTIES OF THE RING ELECTRON.

THE MASS OF THE ELECTRON.

The electron was originally regarded as a sphere or spheroid, and in this case the electromagnetic mass may be calculated as was first shown by J. J. Thomson. The electromagnetic inertia for the slowly moving sphere, charge e, radius a, is $2e^2/3ac^2$, where c is the velocity of light.† For the Lorentz electron, for which the shape alters as the acceleration proceeds, the longitudinal and transverse masses are equal to

$$2e^2/3ac^2(1-k^2)^{3/2} \text{ and } 2e^2/3ac^2(1-k^2)^{1/2}$$

(where k denotes the ratio of the speed of the centre to that of light), as required by the Principle of Relativity.‡

The question of the electromagnetic mass of the ring electron has been discussed by Webster,§ who has shown that the relativity principle requires certain assumptions about the internal energy, which, when made in the most plausible way, lead to the result that the mass of the electron is $2/c^2$ times its electrostatic energy. In ordinary units the mass is given by

$$M=\frac{e^2}{\pi c^2 R}\log\frac{8R}{R'},$$

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* W. C. McC. Lewis, "Phil. Mag.," Vol. XXVIII., p. 104, 1914.

† *See* Schott, "Electromagnetic Radiation," Appendices C and D.

‡ Schott, "Proc." Roy. Soc., Vol. XCIV., p. 422, 1918.

§ Webster, "Phys. Rev.," Vol. IX., p. 484, 1917.

where R is the radius of the ring, and R' is the radius of the cross-section of the ring. This makes the radius of cross-section extremely small in comparison with the radius of the ring.

The same assumptions lead to the conclusion that the gyroscopic properties of the ring electron are exactly those of a classical electron in an orbit having the same magnetic moment.

THE MAGNETIC MOMENT OF THE RING ELECTRON.

For simplicity we may suppose that the electron is composed of a charge e distributed round a circle of radius a, and moving with angular velocity ω. Then the moment of the equivalent simple magnet is $\frac{1}{2}ea^2\omega$. If m denote the electromagnetic mass of the electron, its angular momentum will be proportional to $ma^2\omega$. Thus, the magnetic moment will be proportional to the angular momentum multiplied by e/m. The quantum theory indicates $h/2\pi$ as the angular momentum, and *assuming the factor of proportionality to be* $\frac{1}{2}$, the magnetic moment is found to be $92{\cdot}7 \times 10^{-22}$ E.M.U.

The magnetic moment of the magneton of Weiss is $18{\cdot}54 \times 10^{-22}$, which is exactly 1/5 of the number given above. It is to be noted that the magneton of Weiss "is not in any way identified with the electron, but is an empirical quantity derived directly from the magnitudes of the susceptibilities of paramagnetic elements and compounds, and for such substances only; it has no meaning for diamagnetic substances." (Parson, p. 76). Thus, the magneton is purely empirical, and not a mechanistic conception. In another place,* however, the author has suggested that it may arise as a difference effect.

Parson has given an estimate of the radius of his magneton, starting from the assumption that the positive sphere of a large atom is nearly proportional to its "magneton number." He concludes that the radius of the magneton is about $1{\cdot}5 \times 10^{-9}$ cm. Assuming further that the velocity at the circumference of the magneton is equal to the velocity of light, the magnetic moment $= \frac{1}{2}eac = 3{\cdot}5 \times 10^{-19}$ E.M.U. This is far larger than the magnetic moment of the Iron atom in the metal at saturation for which the value is 2×10^{-20} only; but on Parson's theory no atom, however many magnetons it contains, can have a moment greater than that of one magneton, and the moment of most atoms will be very much less than this, because the force between the magnetons in an atom will always tend to orient them, so as to make their resultant moment zero.

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* H. S. Allen, "Phil. Mag.," Vol. XXIX., p. 718, 1915.

S. B. McLaren * found that a magneton of any cross-section or aperture has an angular momentum about its axis of $(8\pi^2 c)^{-1} N_e N_m$, where c is the velocity of light, N_e is the number of tubes of electric induction terminating on the surface, and N_m is the number of tubes of magnetic induction passing through the aperture. The applications which McLaren proposed to make "to the theory of complete radiation, spectral series, and the asymmetrical emission of electrons in ultra-violet light" were apparently never published.

CONCLUSION.

If the arguments in favour of a ring electron prove convincing, an important conclusion follows as to the central portion of the atom. The facts of radioactivity indicate that β particles have their origin in the nucleus of the atom. If, then, ring electrons are present near the centre of the atom it will be necessary to revise the prevailing view as to the small size and purely electrostatic field of the nucleus. I have suggested previously that the core of a terrestrial atom is large enough to exert appreciable magnetic forces. This is a natural assumption to make when the core contains both ring electrons and positive units, whatever may prove to be the nature of the latter. In this case it is no longer necessary to postulate the large positive sphere of the Kelvin-Thomson atom, which has been employed in Parson's theory. When the effect of the magnetic core is taken into account, the difficulty found by Parson of reconciling Moseley's atomic numbers with the number of magnetons in the atom disappears.

"To the physicist a theory is a policy rather than a creed." The ring electron not only serves the purpose of explaining known results, but suggests further lines for investigation and experimental research.

In conclusion, I should like to emphasise the fact that when electrostatic forces alone are considered, it is impossible

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* "Phil. Mag.," Vol. XXVI., p. 800, 1913; "Nature," Vol. XCII., p. 165, 1913.

to secure stationary electrons such as seem required in order to explain the facts of valency and stereochemistry, and the results of Compton and Rognley.

On the other hand, when magnetic forces alone are considered it is necessary to postulate molecular magnetic fields of extremely large intensity (10^7 gauss, Oxley and Weiss).

These difficulties may be overcome at one and the same time by assuming the action of both electrostatic and magnetic forces in connection with the core of the atom and the electron. We may then introduce stationary electrons exerting both electrostatic and magnetic attractions and repulsions. The energy of the molecular field would be partly electric partly magnetic.

It remains to reduce the theory to a quantitative form by determining the magnetic moment of the ring electron and that of the core of the atom, and then separating the local molecular field due to the magnetic action from that due to electrostatic action.

ABSTRACT.

Dr. H. S. Allen discussed the arguments in favour of an electron in the form of a current circuit capable of producing magnetic effects. Then the electron, in addition to exerting electrostatic forces, behaves like a small magnet. The assumption of the ring electron removes many outstanding difficulties :—

(1) There is no loss of energy by radiation as in the case of a classical electron circulating in an orbit.

(2) Diamagnetic atoms must have a zero resultant magnetic moment. This is difficult to account for with electrons in orbital motion.

(3) The ring electron gives a good explanation of the facts of paramagnetism, including the experimental results of K. T. Compton and Trousdale, and of A. H. Compton and O. Rognley obtained by X-ray analysis.

(4) The asymmetry of certain types of radiation can be accounted for (A. H. Compton).

(5) The effect of the magnetisation of iron upon its absorption coefficient for X-rays observed by Forman is explained.

(6) The small amount of ionisation of gases produced by X-rays may receive an explanation.

(7) Grondahl claims to have found evidence for a magnetic electron in certain thermoelectric effects.

(8) Webster has given a method of deducing Planck's radiation formula by making certain assumptions as to the internal mechanism of Parson's "magneton."

(9) It is suggested that Bohr's theory as to origin of series lines in spectra may be restated so as to apply it to the ring electron. The essential points of the quantum theory and Bohr's equations may be retained, even if his atomic model be rejected.

(10) If radiation is due to pulsations in a ring electron the Zeeman effect may be deduced by reasoning similar to that first employed by Lorentz.

(11) The scattering of streams of electrons from the sun due to electrostatic forces would be to some extent diminished.

(12) Parson has shown that many of the problems of chemical constitution and stereochemistry may be solved by a magneton theory of the structure of the atom. *Stationary* valence electrons are possible.

(13) The forces of cohesion in a solid are similar in nature to chemical forces, both sets of forces having an electromagnetic origin.

The questions of the mass and magnetic moment of such a ring electron were discussed. It was pointed out that the adoption of this hypothesis would lead naturally to the acceptance of an atomic model with a magnetic core as previously suggested by the speaker.

DISCUSSION.

Dr. D. Owen expressed regret at the unavoidable absence of Prof. Nicholson. His contributions on the subject of atomic structure have already won an important place, and his participation in this discussion had been looked forward to with much interest. Dr. Allen has marshalled a number of lines of argument in favour of the conception of the ring electron. The evidence on the whole scarcely impresses as convincing. Whilst from the point of view of certain phenomena a strong case may be made for its acceptance, it seems equally true that in regard to other phenomena a strong case may be made against.

The hypothesis of the ring electron was proposed by Parson in 1915, in a paper eminent for its lucidity of style, and for the fairness of treatment of prior views of the electron, and it related problems which arise in the investigation of atomic structure. The hypothesis meets with its most striking success on the side of its chemical application. It opens a wider range of interpretation of the chemical bond, explaining, for instance, not only the attraction of different atoms as in a molecule of HCl, but also the attraction of atoms of the same kind, each electrically neutral, as in a molecule of hydrogen. The property of high stability of the group of eight ring electrons arranged in cubic order is decidedly interesting, and appears to meet in a simple and satisfactory way the Law of Octaves apparent in the arrangement of the atoms in order of ascending atomic weight. Another feature is that places are reserved for six elements lying between hydrogen and helium. It is unfortunate that none of these places has yet been filled. The one immediately below helium, termed protofluorine, might well have been expected to reveal itself in virtue of its possession of a unit valency. Parson, however, is only able to remark that its absence must be assigned to causes at present unknown. It would be premature to claim Coronium and Nebulium for any of these places.

Again, in reference to radiation, one of the chief advantages claimed for the ring electron is that it avoids the difficulty arising from the excessive rate of radiation of the atoms of the lightest elements on a particle-electron hypothesis. The ring electron will not radiate at all. But then the atom does radiate! How is the ring electron to permit of this? Not, apparently, without the aid of supplementary hypothesis, tending to rob the hypothesis of its engaging simplicity. The conclusion may perhaps now be accepted as certain that there are circumstances in which the Newtonian mechanics do not hold (*vide* Jeans' Report on

Radiation and the Quantum Theory, published by this Society). This is a general consideration which may have application in solving the difficulties connected with radiation as treated by the ordinary electrodynamic theory.

Judged by its power of predicting new phenomena, the hypothesis of the ring electron is disappointing. Apart from the insertion of new elements of low atomic weight, the fresh phenomena which it points to are only of a secondary order, difficult to place in evidence and of little consequence if verified. In striking contrast is the fertility of Bohr's hypothesis of the atomicity of angular momentum, leading to the prediction of a hitherto unobserved spectral series, a prediction swiftly verified by the observations of Lyman.

Thus, on the whole, the ring electron cannot yet be said to have shown its capacity of rising to the highly responsible duties imposed upon it by the varied atomic phenomena which it is called upon to explain and correlate.

Dr. W. Wilson said that the question of the energy loss by radiation was not really a difficulty in the case of the classical electron. We were obliged to keep to the quantum theory because it was impossible to deduce Planck's law without departing from the old dynamics, or rather, introducing special types of constraint. Now, on the quantum theory, the electron was capable of travelling in a stationary orbit for finite periods without radiating.

We might introduce ring electrons to account for paramagnetism with another group of electrons giving electrical conductivity.

Prof. Nicholson's contention that co-planar rings of electrons were impossible was founded on the old dynamics; but it was unsound to apply the old criteria for stability. On the basis of the quantum theory he thought it might be possible to have co-planar rings.

He did not think it was possible to draw the conclusion that cohesive forces are electromagnetic from Michelson and Morley's experiment.

Prof. Hale (of Mount Wilson Observatory) said he would take this opportunity of thanking the Physical Society of London for the Honorary Fellowship conferred on him some years ago. He would not venture to discuss the constitution of the electron but would refer to some solar pheomena which might be of interest in connection with it.

There were two classes of magnetic phenomena in the sun. In spots there were intense magnetic fields of 5,000 units or so extending over considerable areas, and there was no very clear explanation of the manner in which the necessary separation of charges occurred. If the separation were considerable one would expect some evidence from the Stark effect. A very careful search for this had been made but without result. With iron they had investigated the Stark effect in the laboratory and attempted to compare it with spot phenomena, and found that the electric field must be less than 200 units.

The general magnetic field of the sun is so small that the total displacement of spectrum lines is only about 1/1,000 A.U., *i.e.*, the maximum intensity is about 50 units. Its polarity is the same as that of the earth, and the magnetic poles are 6½ deg. from the axis. The field diminishes rapidly above the surface. It is undetectable at a height of 1,000 to 2,000 miles.

The President reminded the meeting of the observations of Rutherford and his pupils on the scattering of α-particles by matter. These observations led Rutherford to substitute the atom with a positive nucleus for the Kelvin-Thomson atom. As Dr. Allen had not mentioned the subject he would like to ask whether the ring electron would give the scattering found by experiment.

Mr. J. H. Jeans (communicated): Since the appearance of Weber's theories of magnetism (1852), physicists have had every reason to expect that the phenomena of magnetism would prove to be traceable to charges of electricity describing orbits of at most molecular magnitude. The recent discovery that not only the charges on electrons are "atomic," but that there is some kind of "atomicity" in their very motions leads naturally to the supposition that some kind of atomicity is to be expected in magnetic phenomena. This atomicity has been revealed by the researches of Weiss and Parson.

It is natural to try to construct a model which shall explain the mechanism of this atomicity. The model which most obviously suggests itself is the ring electron. So long as this model fails to fit in with all known physical facts it cannot be regarded as an expression of ultimate truth; it will remain merely a model, making no claim to uniqueness, and its value will be judged by the number and importance of the facts that it accounts for and by the ability it shows to predict undiscovered phenomena, or to suggest new lines of research.

The ring electron does not appear to have been especially fortunate in this latter respect, and its claim to consideration must perhaps rest mainly on arguments such as those marshalled by Dr. Allen. In considering a claim of this kind it must always be taken for granted that the proposed model will explain at least one or two facts perfectly. The model has been devised *ad hoc.* What we have to examine is whether it explains other extraneous facts, and particularly whether it does so without destroying more of the old fabric of science than it builds of new.

It is to be feared that Dr. Allen's claim that the ring electron does not lose energy by radiation will not help it. An electron of the old-fashioned kind did not lose energy by radiation, unless it was accelerated in space, and a ring electron, when accelerated in space will lose precisely the same amount of energy as the old-fashioned electron. The fact that the ring electron, rotating freely and with its centre of gravity unaccelerated, does not lose energy, is not an argument in favour of the ring electron, because any number of electrons can be devised having the same advantage. But, according to the classical dynamics, the kinetic energy of translation of a system of ring electrons would soon be degraded into radiation, and nothing short of the abandonment of the classical system of dynamics will provide a way out of the difficulty.

Dr. Allen's suggestion that Bohr's theory of spectral series might be restated in terms of the ring electron would seem to require that the radius of the electron should replace the radius of the orbit considered by Bohr. The atom with one electron must consist of a ring electron with a nucleus at the centre of the ring, a rearrangement of the atom which appears to do more harm than good. The nucleus is now brought to rest in the atom instead of describing an orbit of extremely small radius. But it is just the description of this very small orbit by the nucleus that results in the variations of the Rydberg constant. These variations enabled Fowler to determine the mass-ratio of electron to hydrogen nucleus to be 1/1836, a determination which must be regarded as purely illusory if the nucleus is to be put at the centre of the electron. Similarly, the recent work of Sommerfeld on the structure of spectral lines seems to admit of no interpretation in terms of the proposed new conception of the atom.

Prof. Webster and Dr. Allen suggest that the ring electron shows special aptitude for explaining Planck's law of radiation. But in this respect the ring electron is like any other system—if it is assumed to obey Planck's dynamical laws, it will give Planck's radiation formula, and if it is assumed to obey the classical laws, it will give the equipartition (Rayleigh-Jeans) formula. Different radiation formulæ in a state of thermodynamical equilibrium are associated with different systems of dynamical laws, not with different systems of mechanical models.

It appears, then, that the ring electron may be welcomed mainly as giving a vivid picture of certain magnetic phenomena. There seems to be no clearly established case in which it successfully explains any phenomenon outside magnetism, and it is quite out of the question to suppose that the ring electron is going to reconcile the classical dynamics with phenomena which are demonstrably inconsistent with the classical dynamics.

Prof. J. W. **Nicholson** (communicated): Whatever may be thought regarding the existence or non-existence of a ring electron, and whatever our views may be as to the utility of ascribing defined structure to an electron in the present stage of our knowledge, it must be admitted that Dr. Allen, by collecting together these various isolated and sometimes obscure and little known results, which of course in some cases require further verification, has rendered an important service which it has for some time been necessary to undertake. That the same cause, whatever it may be, is the basis of several of them has been rendered fairly clear. Personally I prefer, like Dr. Allen, to keep an open mind, but at least we must take the ring electron seriously on account of the great elegance of the treatment which can be applied to it and of some of its properties. At the same time, I cannot claim to be one of its supporters as a physical entity with the evidence at present available, in spite of the admiration we must all feel for some of the work to which its introduction has led. As regards detailed discussion of Dr. Allen's Paper, I do not feel that I have much to say. He has presented the case very impartially, and indicated where necessary the possible doubt which can be thrown on individual phenomena which have been claimed to exist. He has, in fact, left us very little that can be said on the subject proper, though on other issues which arise in connection with it very much might be said. I must, however, confine myself to one or two points.

One of the most fundamental difficulties of all the more recent views on the atom is that presented by magnetic phenomena. The quantum view is peculiarly at fault here in its present form, and some essential modification must be made. The neglect by all but spectroscopists, of the theory of Ritz on the origin of spectral series—not that I believe in it as it stands—is astonishing. This theory, while on a clear magnetic basis which is quite precise, has predicted spectral series and laws of spectra to an extent which the quantum theory cannot at present approach, and continues to do so. It must be borne in mind steadily by every spectroscopist—and, in fact, is at the basis of every new spectrum discovered as a regular series—while it can, given two series of an element, predict all the others. It can never be superseded as an effective prophet. Bohr's quantum theory is, of course, another prophet which has been effective over a small range. The difficulty is to extend it. Recently it apparently became possible in the hands of Sommerfeld to explain the structures of some of the simpler spectral lines on the hypothesis that the separation in H_β had the same frequency as that in H_α—in other words, that Balmer's series was a Diffuse series. Dr. Merton and myself made an experimental investigation to test this point, published in the "Phil. Trans." It turned out to be untrue. After verifying Michelson and Buisson and Fabry's value for the separation of H_α, we passed on to that of H_β, which was found to be of a different order, and, in fact, of exactly the amount required by a Principal, not a Diffuse series. The present theory of spectral *structure*, as distinct from distribution of lines, is thus very unsatisfactory, and must at least be re-cast in some form not at present evident.

The quantum theory, therefore, is rendered even more tentative, and great caution is necessary in making fresh hypotheses regarding the atom in order to extend its interpretation to other phenomena, though I confess to a vivid interest in such efforts and also to a share in them myself.

Dr. Wilson and others have referred to the vexed question of coplanar rings of electrons, and the point at which ordinary dynamics breaks down in the atom. That a breakdown of the dynamics of matter in bulk does occur is certain, but hardly unexpected when we proceed to the unit of matter. The quantum theory is not, in fact, such a startling revolution as it at first seemed. Those who speculate on the electron, and to a much less extent the atom, are in the same position as the ancients who speculated on the structure of matter in bulk.

I do not feel justified in going far on this occasion into the coplanar ring question. Its impossibility as an atomic structure is not, in fact, confined to the old dynamics. It permeates most of the obvious extensions of Bohr's new dynamics, from the hydrogen atom to the more complex ones, and is a fundamental difficulty even in the hydrogen molecule. What I have said may, however, be sufficient to show my belief that speculation on such questions as the ring electron is as essential to future development as the raising up of a quantum theory of the atom. We must continue to trace the career of any theory as a prophet until its abandonment becomes imperative, whether we are in any sense a believer in that prophet or not.

Sir JOSEPH LARMOR (communicated): Dr. Allen argues in an interesting way for an amperean molecular permanent current as the ultimate element. In early days that was attractive. In the form of a fluid vortex carrying an electric charge its relations of stability were discussed by Pocklington in the "Philosophical Transactions" about 20 years ago. The objection is that it is not a physical unit. A vortex ring can represent a magnet as regards its field, and the forces between magnets *except as to sign*, but electric attraction is not provided for unless by adding an attracting charge. An electron is a physical conception complete and self-contained. One or more electrons constrained to move round a channel would be like an amperean current. It is not unlikely that constraint of this kind will have to be introduced into molecular models, to give an account of paramagnetism and ferromagnetism—namely, structure in space or atom involving channels more or less definite for the electrons to circulate in.

Dr. ALLEN, in reply, said that reference had been made to the mass of the positive part of the atom. It was not necessary to postulate a very small nucleus to account for the electromagnetic mass of the whole atom. The core might be complex and contain both electrons and α-particles; or the H atom itself might be built up of positive electrons, and it would be to those that we must attribute the small mass.

As regards scattering, Rutherford's deductions were inconclusive, as he had attended only to electrostatic forces. If magnetic fields were also considered it was possible to account for the scattering phenomena without assuming a very small nucleus. Then there was the question of where the Newtonian dynamics broke down. On Bohr's theory, this must occur somewhere between the electron and the core of the atom. If we adopt the ring electron in conjunction with a magnetic core, we may say that the Newtonian dynamics breaks down within the electron. Personally, he did not accept Parson's theory as it stood; but although the ring electron was essential to Parson's theory, that theory with its distributed positive sphere was not essential to the ring electron.

III. *Relativity and Gravitation.* By WILLIAM WILSON, *Ph.D., D.Sc., University of London, King's College.*

RECEIVED OCTOBER 21, 1918.

THE theory of relativity was greatly simplified by Minkowski,* who perceived that the equations of transformation (the Lorentz transformation) from a system S to another S', moving relatively to S with a uniform velocity, were precisely the extension to a four-dimensional world of a change of axes in three dimensions. The metrical properties of this Minkowskian four-dimensional world are similar to those of three-dimensional Euclidean space. In particular the square of an element of length in it has the form

$$ds^2=dx^2+dy^2+dz^2+du^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where dx, dy, dz, du may be termed the projections of ds on the respective co-ordinate axes.

Recently Einstein,† making use of speculations of Riemann,‡ has given a theory of gravitation the basis of which consists in assuming a more general form for the square of the element of length in the four-dimensional space-time manifold, namely,

$$ds^2=\sum_s\sum_t g_{st}dx_s dx_t, \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$s=1, 2, 3, 4$$

$$t=1, 2, 3, 4,$$

where dx_1, dx_2, &c., are now written instead of dx, dy, &c. The 16 coefficients g_{st} are the components of a covariant tensor of the second order, and functions of the x_s. The 16 products $dx_s dx_t$ are the components of a contravariant tensor of the second order. The equations which Einstein deduces for the motion of a particle in a gravitational field are given by Dedekind in a note at the end of one of Riemann's papers.§ What is new in Einstein's work is the application which is made of Riemann's ideas, and also the mode of determining the coefficients g_{st}.

The purpose of the present communication is to show that the equations of motion of a particle in a gravitational field can be put in a Hamiltonian form, that is to say, in the form,

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* "Raum u. Zeit.," published, together with Papers by Lorentz and Einstein, in a volume entitled "Das Relativitätsprinzip," Leipzig, 1913.

† Einstein, "Die Grundlagen d. allgemeinen Relativitätstheorie," "Ann. d. Physik," XLIX., p. 769 (1916).

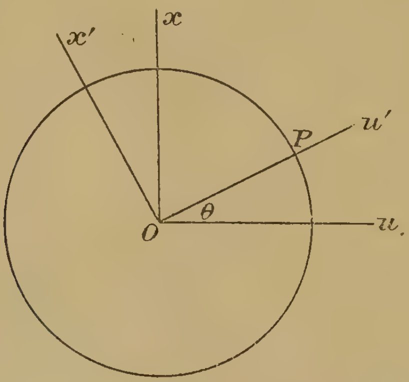
‡ Riemann, "Ueber die Hypothesen, welche der Geometrie zu Grundeliegen," "Ges. Werke," Leipzig, 1876, p. 254.

§ Riemann, "Commentatio mathematica," &c., "Ges. Werke," p. 388.

$$\left.\begin{aligned} \frac{dp_s}{d\tau} &= -\frac{\partial H}{\partial x_s}, \\ \frac{dx}{d\tau} &= \frac{\partial H}{\partial p_s}, \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where the p_s are the components of a covariant four-vector, which may be termed the momentum of the particle, and H is a function of the p_s and x_s. The independent variable, τ, is the exact analogue of Minkowski's "Eigenzeit," the meaning of which will appear in what follows.

A very brief account of the older (Minkowskian) form of relativity, more particularly in regard to its bearing on the subject of the present Paper, will be of assistance. Let us suppose there are two systems, S and S', on which are observers provided with similar physical measuring apparatus, the system S' moving with a uniform velocity, v, relative to S. In order to simplify our statements, let us further suppose that the sets of axes of co-ordinates in S and S' to which the observers refer their measurements are so chosen as to fulfil the following conditions :—



1. They exactly coincide at the time $t=t'=o$, where t and t' represent the time as measured by the observers on S and S' respectively.

2. The directions of the axes are such that the velocity of S' relatively to S is in the (common) x or x' direction.

If, now, we define u by the equation,

$$u^2 = -c^2t^2,$$

where c is a universal constant—the velocity of radiation in empty space, all the postulates of the older form of relativity can, I think, be comprised in the single statement,

$$x^2+y^2+z^2+u^2=x'^2+y'^2+z'^2+u'^2, \quad \ldots \quad (4)$$

where x, y, z, u is a point-instant referred to the system S and x', y', z', u' the same point-instant referred to S'. If, for example, a light pulse is emitted at the time $t=t'=0$ from the common origin of S and S' then we have for any point reached by the disturbance,

$$x^2+y^2+z^2+u^2=0,$$

$$x'^2+y'^2+z'^2+u'^2=0,$$

or,

$$x^2+y^2+z^2=c^2t^2,$$

$$x'^2+y'^2+z'^2=c^2t'^2.$$

The light will spread out in the form of a spherical shell with the same velocity c for both sets of observers; and each set of observers will regard the origin of their set of axes as the centre of the shell.

The simplest and, I think, from the point of view of the physicist, the only satisfactory way of satisfying the postulate (4) consists in putting

$$y=y',$$

$$z=z',$$

and consequently,

$$x^2+u^2=x'^2+u'^2.$$

So that (x, u) are related to (x', u') in the same way as the rectangular co-ordinates of a point, referred to two sets of axes of co-ordinates, in plane geometry.

Consider a point P fixed in S', whose S' co-ordinates are o, y', z', u' (*see* Figure). In the system S its co-ordinates will be x, $y=y'$, $z=z'$ and u. Let θ be the (imaginary) angle between u and u', then clearly

$$\left.\begin{aligned} x' &= x\cos\theta - u\sin\theta, \\ u' &= x\sin\theta + u\cos\theta. \end{aligned}\right\} \quad \ldots \quad (5)$$

Now, v, the velocity of P relative to the system S, is expressed by

$$v=\frac{x}{t}.$$

Therefore,

$$\frac{v}{ic}=\frac{x}{u},$$

or,

$$\frac{v}{ic}=\tan\theta.$$

It is convenient to use the letter γ to denote $\cos\theta$, so that

$$\gamma=\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}},$$

and

$$\sin\theta=\gamma\frac{v}{ic}.$$

The equations (5) become, on substituting for $\cos\theta$ and $\sin\theta$

$$x'=\gamma(x-vt),$$

$$t'=\gamma\left(t-\frac{vx}{c^2}\right),$$

and if we add

$$y'=y,$$
$$z'=z,$$

we have the equations of the Lorentz transformation. This view of the Lorentz equations as a transformation from one set of axes to another in a 4-dimensional space-time manifold constitutes, I believe, the essential part of Minkowski's contribution to the theory of relativity.

MINKOWSKIAN DYNAMICS OF A PARTICLE.

The equations of motion of a particle are

$$\left.\begin{aligned}\mu\frac{d^2x}{d\tau^2}&=f_x,\\ \mu\frac{d^2y}{d\tau^2}&=f_y,\\ \mu\frac{d^2z}{d\tau^2}&=f_z,\\ \mu\frac{d^2u}{d\tau^2}&=f_u,\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where μ is an invariant coefficient, which for the sake of simplicity we shall suppose to be constant. It can be identified with the mass of the particle when at rest or in very slow motion. The quantity, τ, is Minkowski's "Eigenzeit," mentioned above, and is defined by

$$ds^2=-c^2d\tau^2.$$

The f_x, f_y, f_z, f_u are the components of a 4-vector—the force 4-vector. We deduce from (6)

$$\frac{\mu}{2}\frac{d}{d\tau}\left(\frac{ds}{d\tau}\right)^2=f_x\frac{dx}{d\tau}+f_y\frac{dy}{d\tau}+f_z\frac{dz}{d\tau}+f_u\frac{du}{d\tau},$$

and since $\frac{ds}{d\tau}$ is constant we have

$$0=f_x\frac{dx}{d\tau}+f_y\frac{dy}{d\tau}+f_z\frac{dz}{d\tau}+f_u\frac{du}{d\tau},$$

a result which can be expressed by saying that the force 4-vector is orthogonal to the velocity (or displacement) 4-vector. If we substitute $\mu\frac{d^2u}{d\tau^2}$ for f_u we get

$$-\mu\frac{du}{d\tau}\quad\frac{d^2u}{d\tau^2}=f_x\frac{dx}{d\tau}+f_y\frac{dy}{d\tau}+f_z\frac{dz}{d\tau};$$

and remembering that

$$\frac{du}{d\tau}=ic\frac{dt}{d\tau}=ic\gamma,$$

we have

$$\mu c^2\gamma\frac{d\gamma}{d\tau}=f_x\frac{dx}{d\tau}+f_y\frac{dy}{d\tau}+f_z\frac{dz}{d\tau}\quad . \quad . \quad . \quad . \quad (7)$$

It is usual to identify f_x/γ, &c., with the components of the Newtonian force acting on the particle. If we denote them by P_x, P_y, P_z, we have, from (7),

$$d(\mu c^2\gamma)=P_xdx+P_ydy+P_zdz;$$

a result which expresses the energy principle. The energy of the particle is, therefore, if we omit an arbitrary constant,

$$E=\mu c^2\gamma.$$

The product, $\mu\gamma$, is the ordinary or "transverse" mass of the particle. Denoting this by m, we have

$$mc^2=E,$$

a result first given by Einstein.* The kinetic energy of the particle is

$$\mu c^2(\gamma-1),$$

* Einstein, "Ann. d. Physik," XVII., p. 891 (1905).

since it must vanish with zero velocity. Since (7) can be put in the form,

$$d\left(\frac{\mu\gamma^2c^2}{2}\right)=f_x dx+f_y dy+f_z dz,$$

the possibility of identifying $\frac{\mu\gamma^2c^2}{2}$ with the energy of the particle suggests itself. This does not seem to have been pointed out before. The kinetic energy would then be

$$\frac{\mu c^2}{2}(\gamma^2-1).$$

Both expressions for the kinetic energy reduce to the ordinary one for small velocities as may be readily verified by substituting $(1-v^2/c^2)^{-\frac{1}{2}}$ for γ. The second expression, it may be noted, can also be written in the form

$$\frac{\mu}{2}\left(\left(\frac{dx}{d\tau}\right)^2+\left(\frac{dy}{d\tau}\right)^2+\left(\frac{dz}{d\tau}\right)^2\right).$$

MOTION OF A PARTICLE ON WHICH NO FORCE IS ACTING.

This brief outline of the foundation of Minkowski's theory of relativity (as I interpret it) may be concluded by the consideration of a case which, though very simple, is highly important, since it is the exact analogue in the older relativity to the case of the gravitational motion of a particle in the newer or more general form of relativity.

Let p_x, p_y, &c., denote the components of the momentum 4-vector of the particle, so that we have

$$p_x=\mu\frac{dx}{d\tau}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and three similar equations. We may define a function E (not the same as the previous function E) by

$$2E=p_x\frac{dx}{d\tau}+p_y\frac{dy}{d\tau}+p_z\frac{dz}{d\tau}+p_u\frac{du}{d\tau}, \quad . \quad . \quad . \quad (9)$$

so that

$$E=\frac{\mu}{2}\left(\frac{ds}{d\tau}\right)^2,$$

or

$$E=-\frac{\mu}{2}c^2,$$

and

$$\frac{dE}{d\tau}=0.$$

We may also write

$$E \equiv H = \frac{1}{2\mu}\left[p_x^2 + p_y^2 + p_z^2 + p_u^2\right]. \quad . \quad . \quad . \quad . \quad (10)$$

In the simple case under consideration we have

$$\frac{dp_x}{d\tau} = -\frac{\partial H}{\partial x},$$

$$\frac{dx}{d\tau} = \frac{\partial H}{\partial p_x},$$

together with three similar pairs of equations for the y, z and u axes.

RELATIVITY AND GRAVITATION.

The Minkowskian form of relativity is a special case of the more general relativity introduced by Einstein. In this latter the square of the element of length is expressed by equation (2). Here again we shall define τ by the equation,

$$ds^2 = -c^2 d\tau^2,$$

where c is precisely the same invariant constant as before, though it does not now represent the velocity of light in empty space, except in the special case where

$$g_{st} = 1 \text{ for } s = t,$$

and $$g_{st} = 0 \text{ for } s \neq t.$$

We shall also define the function E for a particle by

$$E = \frac{\mu}{2}\left(\frac{ds}{d\tau}\right)^2,$$

or $$E = -\frac{\mu}{2}c^2.$$

The definition of the momentum of the particle (8) must now be replaced by

$$p_s = \sum_t \mu g_{st}\frac{dx_t}{d\tau}, \quad t = 1, 2, 3, 4 \quad . \quad . \quad . \quad . \quad (8')$$

The p_s are the components of a covariant 4-vector. We have therefore

$$\sum_s p_s \frac{dx_s}{d\tau} = \sum_s \sum_t \mu g_{st}\frac{dx_s}{d\tau}\,\frac{dx_t}{d\tau} \quad \begin{matrix} s = 1, 2, 3, 4, \\ t = 1, 2, 3, 4, \end{matrix}$$

and, therefore, by (2)

$$\mu\left(\frac{ds}{d\tau}\right)^2=\sum_s p_s\frac{dx_s}{d\tau},$$

so that

$$2E=\sum_s p_s\frac{dx_s}{d\tau},\quad s=1, 2, 3, 4. \quad . \quad . \quad . \quad (9')$$

If we write out the equations (8′) and solve for $dx_t/d\tau$, we get

$$\frac{dx_t}{d\tau}=\frac{1}{\mu}\sum_s p'_s\frac{G^{st}}{|g|},$$

where $|g|$ is the determinant whose constituents are the g_{st} and the G^{st} are the minors corresponding to the g_{st}. If we write

$$g^{st}=\frac{G^{st}}{|g|},$$

we have

$$\frac{dx_t}{d\tau}=\sum_s\frac{p_s}{\mu}g^{st}.$$

Obviously

$$\sum_s\sum_t g_{st}g^{st}=4,$$

and

$$\sum_s g_{sm}g^{sn}=1 \text{ or } 0,$$

according as m and n are equal or unequal. The coefficients g^{st} are the components of a contravariant tensor of the second order.

If we substitute the expression we have found for $\frac{dx}{d\tau}$ in (9′), we obtain

$$E\equiv H=\sum_\kappa\sum_\Lambda\frac{p_\kappa p_\Lambda}{2\mu}g^{\kappa\Lambda}\begin{matrix}\kappa=1, 2, 3, 4\\ \Lambda=1, 2, 3, 4\end{matrix}. \quad . \quad . \quad (10')$$

Where the $g^{\kappa\Lambda}$ are functions of the x_s. If a few of the terms of H are written out and differentiated partially with respect to p_s we easily find

$$\frac{dx_s}{d\tau}=\frac{\partial H}{\partial p_s},\quad s=1, 2, 3, 4,$$

and since

$$\frac{dE}{d\tau}=0,$$

we have

$$\sum_s\left\{\frac{\partial H}{\partial p_s}\frac{dp_s}{d\tau}+\frac{\partial H}{\partial x_s}\frac{dx_s}{d\tau}\right\}=0;$$

whence it follows, on substituting $\frac{dx_s}{d\tau}$ for $\frac{\partial H}{\partial p_s}$ that

$$\frac{dp_s}{d\tau} = -\frac{\partial H}{\partial x_s}, \quad s=1, 2, 3, 4.$$

These are the equations which determine the motion of a particle in a gravitational field. That they are identical with those given by Einstein will now be shown. To begin with, they may be written in the following form :—

$$\sum_t \frac{d}{d\tau}\left(\mu g_{st}\frac{dx_t}{d\tau}\right) + \frac{1}{2\mu}\sum_\kappa\sum_\Lambda p_\kappa p_\Lambda \frac{\partial g^{\kappa\Lambda}}{\partial x_s} = 0,$$

therefore

$$\sum_t \mu g_{st}\frac{d^2x_t}{d\tau^2} + \mu\sum_t \frac{dg_{st}}{d\tau}\cdot\frac{dx_t}{d\tau}$$

$$+\frac{\mu}{2}\sum_\kappa\sum_\Lambda\sum_m\sum_n\left(g_{\kappa m}\frac{dx_m}{d\tau}\right)\left(g_{\Lambda n}\frac{dx_n}{d\tau}\right)\frac{\partial g^{\kappa\Lambda}}{\partial x_s} = 0. \quad . \quad . \quad (11)$$

Since

$$\sum_\Lambda g_{\Lambda n}g^{\kappa\Lambda} = \text{constant},$$

therefore

$$\sum_\Lambda \frac{\partial g_{\Lambda n}}{\partial x_s}g^{\kappa\Lambda} + g_{\Lambda n}\frac{\partial g^{\kappa\Lambda}}{\partial x_s} = 0,$$

and the third term of (11) may be written,

$$-\frac{\mu}{2}\sum_\kappa\sum_\Lambda\sum_m\sum_n g_{\kappa m}g^{\kappa\Lambda}\frac{\partial g_{\Lambda n}}{\partial x_s}\ \frac{dx_m}{d\tau}\ \frac{dx_n}{d\tau},$$

and since

$$\sum_\kappa g_{\kappa m}g^{\kappa\Lambda} = 1, \quad \Lambda = m,$$

$$= 0, \quad \Lambda \neq m,$$

we see that the last term in (11) becomes

$$-\frac{\mu}{2}\sum_m\sum_n \frac{\partial g_{mn}}{\partial x_s}\cdot\frac{dx_m}{d\tau}\ \frac{dx_n}{d\tau}.$$

Equation (11) therefore becomes

$$\sum_t \mu g_{st}\frac{d^2x_t}{d\tau^2} + \mu\sum_t\sum_r \frac{\partial g_{st}}{\partial x_r}\ \frac{dx_r}{d\tau}\ \frac{dx_t}{d\tau} - \frac{\mu}{2}\sum_m\sum_n \frac{\partial g_{mn}}{\partial x_s}\ \frac{dx_m}{d\tau}\ \frac{dx_n}{d\tau} = 0 \quad (11')$$

This may be written in the following more symmetrical way :

$$\sum_t \mu g_{st}\frac{d^2x_t}{d\tau^2} + \frac{\mu}{2}\sum_m\sum_n\left\{\frac{\partial g_{sm}}{\partial x_n} + \frac{\partial g_{sn}}{\partial x_m} - \frac{\partial g_{mn}}{\partial x_s}\right\}\frac{dx_m}{d\tau}\ \frac{dx_n}{d\tau} = 0. \quad . \quad (12)$$

Apart from immaterial details, this is the form in which the equations are given by Einstein and also by Dedekind in the note mentioned above.

If we write the function E in the form

$$E \equiv L = \frac{\mu}{2} \sum_{\kappa} \sum_{\Lambda} g_{\kappa\Lambda} \frac{dx_{\kappa}}{d\tau} \cdot \frac{dx_{\Lambda}}{d\tau},$$

we see that

$$p_s = \frac{\partial L}{\partial \dot{x}_s},$$

where

$$\dot{x}_s = \frac{dx_s}{d\tau},$$

and the equations of motion of the particle may also be written as follows:

$$\frac{d}{d\tau}\left(\frac{\partial L}{\partial \dot{x}_s}\right) - \frac{\partial L}{\partial x_s} = 0, \quad s = 1, 2, 3, 4, \quad . \quad . \quad . \quad . \quad (13)$$

since these equations are identical with (11′). This is the Lagrangian form of the equations.

SUMMARY.

The motion of a particle in a gravitational field is dealt with on the basis of the general theory of relativity, and it is shown that the equations of motion can be stated in the Hamiltonian and Lagrangian forms.

ABSTRACT.

The motion of a particle in a gravitational field is treated from the point of view of the general theory of relativity. It is shown that the equations of motion of the particle can be expressed in the following Hamiltonian form:—

$$\frac{dp_s}{d\tau} = -\frac{\partial H}{\partial x_s},$$

$$\frac{dx_s}{d\tau} = \frac{\partial H}{\partial p_s},$$

where p_s is the s component of the covariant 4-vector momentum, x_s the corresponding positional co-ordinate, and τ the Minkowskian "Eigenzeit." A short outline of the Minkowskian Theory of Relativity is included in the Paper.

DISCUSSION.

Dr. H. S. ALLEN congratulated the author in expressing Einstein's theory in such a comparatively simple way.

Mr. T. SMITH asked what was the physical significance of the quantity H appearing in the equations.

The PRESIDENT asked what physical meaning would be attached to the product $dx_s\, dx_t$ when s and t were different.

Dr. WILSON, in reply, said that the quantity H had the dimensions of energy, and occupied a position in the 4-dimensional space-time manifold, similar to that of the Hamiltonian energy function in classical dynamics. He suggested the possibility that the s component of the co-variant 4-vector momentum p_s of an electron may be equal to eA_s, where A_s is the 4-vector potential in the neighbourhood of the electron and e is its charge. He could not, without taking up a great deal of time, explain the meaning of the terms $g_{st}\, dx_s\, dx_t$, $t = / = s$, in the expression for ds^2.

An Exhibition of Some Experiments on Colour Blindness.

By Mr. C. R. Gibson, *F.R.S.E.*

The apparatus consisted of a lantern to produce a bright beam of white light and a coloured glass which could be slipped in front of it, so as to cut out all the red rays. Various samples of coloured cloths and ribbons arranged in pairs, while quite dissimilar when viewed by the white light, appeared perfect matches with the screen interposed, the conditions then being similar to those in the case of a red blind person. He had found in experimenting with wools by this method that many coloured wools were unsuitable for the purpose on account of fluorescence. Thus, although no red light fell on them from the apparatus, there was plenty of red in the light reflected by the wools. In these cases, in order to see what the colours would appear to the red blind man, it was necessary to have the filter between the wool and the eye, and not simply between the source of light and the wool.

DISCUSSION.

Mr. C. C. Paterson mentioned that in the case of signal lamps it was possible to tell red from green, quite apart from their colour, by looking at them indirectly. A green light got brighter off the line of vision, while a red light got fainter.

Mr. J. Guild asked what screen was employed.

Mr. Gibson said that any screen which cut out the red was suitable. He had tried gelatine dyed with the Sanger-Sheppard minus red. This was good enough for visual work, but not dense enough for the lantern. What he used was practically the ordinary "signal green" glass.

IV. *Note on the Linguistic Nomenclature of Scientific Writers.*

By ALBERT CAMPBELL, *B.A.*

RECEIVED NOVEMBER 22, 1918.

MOST scientific people are agreed as to the importance of clear and consistent nomenclature, for it is generally recognised that irregularity in nomenclature is a great stumbling block to the learner and even to the expert. In mathematics, particularly for the fundamental processes, regularity is of the first importance; it would be intolerable, for example, if we wrote the squares of a, b, c.. as a^2, b^2, c^2.., but those of x, y, z.. as x_2, y_2, z_2... And yet, when we come to linguistic forms, we find that British scientific writers, instead of helping and hastening the natural tendency of our language to become more regular, are actually the chief offenders in introducing irregularity. Except for the barbarous spelling of its written representation (condemned by all modern philologists), our English tongue is fortunately one of the most regular in grammatical form, and this property gives it world-wide power, for it makes it so easily assimilable by other races. But our British scientific writers, when they introduce new terms from Latin or Greek, leave them as unnaturalized aliens, and persist in retaining their foreign plurals, even in cases where the man in the street has already anglicized them.

They say " media, stigmata, formulæ, lacunæ, genera, radii vectores, foci, in vacuo, quanta," and so on; while in ordinary life we say " mediums, formulas, parabolas, premiums, ultimatums, pendulums, in a vacuum, semicolons, crocuses, geraniums, chrysanthemums, syllabuses, (omnibuses), &c." This medieval practice of our writers is certainly confusing to any student who has not had the advantage of a classical education. It is favoured most of all by persons having a smattering of foreign languages or a tendency to pedantry. Anyone who has learned many foreign languages will naturally feel respect for the regularity of our own. In medical science it is obvious that a jargon is useful for the purpose of necessary camouflage, but physicists at least should show a good example by dismissing from use all such pedantic forms. The French, with their instinctive neatness and logicality, are far before us in this respect; they assimilate consistent nomenclature without the slightest difficulty. We have plenty of philologists who, like botanists, observe all kinds of growths, good, bad or indifferent, but we have no language-gardeners who make it their business to trim the hedges and pull up the weeds; our printers and editors, mostly true watch-dogs of reactionary conventionalism, would turn them out as trespassers.

In this connection I should like to add the following

Note on a Name for $2\pi \times$ Frequency.

In English a name has not yet been found for $2\pi n$, where n represents frequency. Many English writers write $2\pi n$ as p, but ω (already used for it when actual angular velocity is implied) is coming to be its internationally used symbol. French writers call it the "pulsation," while the Germans use the term "Kreisfrequenz." The latter word seems fitting, and is more or less self-explanatory; but the term "pulsation" has already a fairly definite meaning, and a careful terminologist ought to limit the meaning of words rather than extend them. I would suggest that it might be called "*pulsatance.*" The termination "ance" brings it into line with words like inductance and reactance. "Pulsatance" appears a convenient and distinctive term; but, however suitable it may be, it stands a very poor chance of being adopted, when we recognize how much the growth of our language has been arrested. During the last 150 years both French and German have very largely increased their vocabularies, while English (relatively) has stood still, except for the addition of technical terms. This deplorable inertia has greatly impeded the introduction of clear and distinctive scientific nomenclature, and it must be got rid of if our scientific language is to keep pace with our advance in knowledge and precision.

ABSTRACT.

The Note insists on the importance of clear and consistent nomenclature and the avoidance of foreign plural forms, such as *media*, *genera*, *radiivectores*, &c. The term *pulsatance* is suggested as a suitable name for $2\pi \times$ frequency.

DISCUSSION.

Mr. A. P. Trotter said that he often thought the valuable work done by Prof. S. P. Thompson, Mr. Duddell and Dr. Russell in connection with the nomenclature of electrical engineering might have been taken up in connection with other sciences. The Americans were coining new scientific terms much too fast—in photometry, for instance—and many required careful definition and the restriction of their use to their proper spheres. The work on the Electrical Engineering Nomenclature Committee had been most interesting, and he thought a small committee of the Physical Society could profitably take the matter up.

Dr. A. RUSSELL congratulated Mr. Campbell on raising an interesting question. Personally he was indebted to Mr. Campbell for many words. As regards classical plurals, it was always rather unpleasant to him to hear words like memorandums, radiuses, &c. Lemma had been mentioned by Mr. Campbell; he always regarded this as being an English word as much as Greek, and thought in most cases it should be left to the literary sense of an author which form of plural to use. As regards ω, this he always looked on as the angular velocity of a rotating vector, and had never found it necessary to use a specific word for it.

Prof. G. W. O. HOWE pointed out that one could not correctly say "an alternating current with an angular velocity ω," since the angular velocity had no reference to the physical alternating current, but only to its graphical representation; one could avoid the difficulty by saying that the current had a frequency $\omega/2\pi$. Some years previously, when he had been on the staff of a firm in Berlin, there was a strong feeling among a number of German engineers against the introduction of non-Germanic technical words. The word Telephon was replaced by Fernsprecher, and objection was taken to such words as booster, the synthetic German compound word being insisted upon. As an indication of the interest taken in such questions, it may be mentioned that, by a mutual agreement among the members of the staff of one department of the works, anyone who at the luncheon table used a word which was not of pure German origin was fined for the benefit of a common fund.

Prof. A. W. BICKERTON said that he had found a serious deficiency in words when working out his new cosmic generalisation, and had found it convenient to coin several new terms. For instance, he had used the word *kinetol* to represent the kinetic energy of unit mass, and *thermatol*, the amount of thermal energy per unit mass, &c.

Mr. C. C. PATERSON said that the termination *-ivity* to indicate a specific quality of a material was one that should be more widely employed. He thought the termination *-ance* should always be carefully limited in its application. It was dangerous to limit the meanings of all words too closely, as there are then no words left for general conceptions. The Americans have already used up nearly all the available terms, and earmarked them for particular meanings. Almost the only one not so treated is *light*.

Prof. LEES said that we appeared to delight in language irregularities. For instance, probably everyone was agreed on the pronunciation of the words *nation*, *national*, but what about the similar pair *ration*, *rational* ?

Mr. T. SMITH (communicated remarks) considered that the note called attention to a matter which had been neglected to a most unfortunate extent. He must plead guilty to having regularly used some of the plurals to which the author took exception, the forms used being, so far as he had noticed, those most frequently employed. A liberal-minded committee charged with the duty of admitting and systematising new scientific words and encouraging their use would be of great assistance at the present time, but there would unfortunately be a considerable risk that a committee appointed for this end would contain a strong conservative element. which would perhaps tend to grow stronger as time went on whose object would be to strangle words struggling for recognition An illustration of the unfortunate tendency in English to combine two words, on one of which a large variety of meanings was thrust, rather than to coin short new words for fundamental ideas, could be drawn from optics. The word *power* was used by itself to denote a definite property of a lens; the same word was also used in *resolving power*, there being no connection between the *powers* in the two cases. Again, *magnifying-power* was used of telescopes and microscopes with different meanings in the two cases. Many other illustrations could be given, but it was clear that the time had come when an attempt should be made to deal with the matter systematically.

Mr. CAMPBELL, in reply, said he had been much interested in the various comments. He would like to draw Mr. Trotter's attention to the work which a nomenclature committee of this society had already done. Dr. Russell's remarks mainly amounted to saying that having done a thing habitually he did not like to change the habit. But very little practice gets over the repugnance. As regards Mr. Paterson's complaint about over-limitation, there were at present too many loosely used words in scientific terminology. For instance, *pressure* had been stolen from dynamics, and used to mean voltage or potential difference. If chemists were to use the same name for different things in this way there would be frequent cases of poisoning. He agreed with Prof. Howe's objection to calling 2π frequency an angular velocity. He was glad to hear Prof. Bickerton's remarks on the need of new terms in astrophysics

V. *A Note on Low-Frequency Microphone Hummers.* By ALBERT CAMPBELL, *B.A.* (*From the National Physical Laboratory.*)

RECEIVED NOVEMBER 22, 1918.

As many people have tried without success to make microphone hummers that would give low frequencies (of the order of 50 to 100 ∾ per sec.), I should like to state the main conditions which I have found to give successful working at the lower frequencies.

1. The natural frequency of the (loaded) diaphragm of a capsule microphone is high, say 1,000 ∾/sec. For the lower frequencies it is desirable to load it with considerable added mass (*e.g.*, a disk of 200 gm.) in order to bring the natural frequency nearer that which is to be generated.

2. The circuit of the maintaining electromagnet which is connected to the secondary of the transformer should have in series a condenser of sufficient capacitance to bring the effective natural frequency of the circuit somewhat near the frequency of the vibrating bar or fork.

For 50 ∾/sec. a capacitance of 20 to 30 μF may be required; the condenser may, however, be made up of a number of small telephone condensers which are very cheap.

In illustration of the effect of tuning the maintaining circuit I may mention the behaviour of a certain microphone hummer having as vibrator a tuning fork of frequency 100 ∾/sec. When the capacitance is sufficiently large the hummer gives 100 ∾/sec. quite steadily, but if the condenser is cut out entirely, the frequency immediately rises to 666, the first harmonic of the fork, and the fundamental entirely disappears.

3. It should always be kept in mind that the ordinary granule microphones (like the "solid-back" type) usually work best when the plane of the diaphragm is not vertical but tilted at a certain angle (sometimes about 40°) to the vertical. In general it is well to mount the microphone capsule in such a way that the angle of tilt can be varied so as to obtain experimentally the best position.

ABSTRACT.

The note describes the conditions of mechanical loading, capacitance and position which the author has found give successful working at low frequencies.

VI. *A Simple Tuning Fork Generator for Sine-Wave Alternating Current. By* ALBERT CAMPBELL, *B.A.* (*From the National Physical Laboratory.*)

RECEIVED NOVEMBER 22, 1918.

AN electrically maintained tuning fork may be used as a source of intermittent current of steady frequency, but the wave form is very far from sinoidal, though no doubt it could be improved by a suitable system of electrical tuning. When only quite a small amount of power is required, the following arrangement forms a convenient source of low frequency current of approximate sine wave form.

To one limb of a fork that can be maintained in the ordinary way there is fastened a small thin coil with its axis at right angles to the direction of motion of the limb. When the fork is vibrating the small coil tends to enter the interpolar space of a permanent magnet fixed to the stand. The voltage induced in the small coil is of approximate sine wave form, and can be varied in amount by altering the position of the magnet or the amplitude of vibration of the fork. The amplitude can be observed by any of the ordinary methods. The total voltage will always be the same when the amplitude and the position of the magnet are fixed. This is convenient for some purposes. Usually the other limb of the fork has to be loaded with a mass similar to that of the small coil. By suitable design of the magnet it is probable that a very pure wave form could be obtained. In the apparatus shown the fork has a frequency of 10 ∾ per sec., and as it has been used in conjunction with vibration galvanometers of this frequency, a few remarks on their behaviour may not be out of place here.

A vibration galvanometer for this low frequency can easily be made to give high sensitivity. For example, with an effective resistance of 1,000 ohms the sensitivity may be 400 mm. at 1 meter distance for 1 microampere. In observing the band of light for a frequency of 10 ∾ /sec., the flicker is very evident, and its presence is advantageous, for, when using a null method, the absence of visible flicker is a very sensitive indication of exact balance. The flicker disappears on the scale when the vibration of the spot is reduced to about 0·1 mm. This was observed with moderate illumination and a scale of distance 2 meters. There is almost the same sensitivity when the light from the mirror is received directly by the eye without any scale at all.

ABSTRACT.

The arrangement consists of an electrically maintained tuning fork, to one prong of which is attached a small thin coil with its axis perpendicular to the direction of motion of the prong. As the fork vibrates the coil oscillates in the field of a fixed horseshoe magnet and an approximately sinusoidal E.M.F. is set up in the coil The frequency with the apparatus shown was 10∿ per second.

VII. *A Method of Comparing Tuning Forks of Low Frequency and of Determining their Damping Decrements.* By ALBERT CAMPBELL, *B.A.* (*From the National Physical Laboratory.*)

RECEIVED NOVEMBER 22, 1918.

FOR tuning forks of low frequency (below 100 ∽/sec.), the audibility is not good, and comparison by the ordinary method of beats is not easy, particularly as the beats may be very slow and hence the counting inaccurate.

The difficulty may be got over by the following simple arrangement. If the two forks to be compared are provided with electromagnets for maintaining them, the windings of these magnets are put in series and connected to a sensitive vibration galvanometer tuned to a frequency near that of the forks. If the forks are set into vibration the beats are clearly shown by the pulsations of the band of light on the scale, and they can be counted with ease and precision. It is best to get the induced voltages (from the electromagnets) nearly equal, for then at each pulsation the galvanometer deflection comes down practically to zero, which gives a point that can be very accurately observed. It is usually not difficult to attain this condition by slightly stopping down the fork that is too vigorous.

The external circuit should be of such resistance that the galvanometer is considerably damped by it; the deflection should fall promptly to zero when the vibration of the forks is suddenly stopped. The above arrangement assumes that the forks are magnetized, which is usually found to be the case with forks that have been electrically maintained. For forks without maintaining electromagnets, the easiest method is to remove the ear-pieces and diaphragms from two telephone receivers and mount their magnets near one limb of each fork. It is improbable that this will seriously affect the frequencies, but I have not yet made any tests on this point.

The vibration galvanometer method is of course applicable to the comparison of steady electric frequencies from any two sources, such as alternators or audions. To compare the frequency of such a source with that of a tuning fork, it is only necessary to induce a very small voltage from the source into the circuit containing the fork magnet and the galvanometer. Two maintained forks similarly may be compared.

Damping Decrement of Fork.

If the magnet of a single fork is connected to the galvanometer, as the vibration of the fork dies down, the galvanometer deflection falls off similarly. The proportionality is probably very close, but in any particular case might want further investigation.

The sensitivity of the galvanometer can be such that there is a considerable deflection when the amplitude of the fork has fallen to a very small amount.

It might be supposed that the power taken in the galvanometer circuit would appreciably increase the damping of the fork, but the following rough calculation shows how very small the effect would be.

If we assume for the fork an effective mass of 200 gm. vibrating with an amplitude of 2 mm. at 50 ∼/sec., the maximum velocity will be about 30 cm. per sec., and the energy nearly 10^5 ergs.

If the whole of this energy were uniformly dissipated by the damping in 200 seconds (a near enough supposition to give the order of the effect), the power spent by the fork would be about

$$50 \ \mu W \text{ (microwatts).}$$

If the galvanometer (not quite in tune) has a sensitivity of 30 mm. at 1 meter for 1 microampere, with an effective resistance of 10 ohms, then for deflection of 60 cm. and 20 ohms in the external circuit the power spent will be about

$$0{\cdot}012 \ \mu W.$$

So the galvanometer circuit takes only about 1/4,000 of the total power lost by damping in the fork; this small effect may in general be neglected.

It can also be shown experimentally that the decrement is practically the same whether the galvanometer circuit is open or closed.

When two forks are compared by the method described above, they form a coupled system linked up by the galvanometer circuit. The preceding calculation shows, however, that the coupling is extremely loose, and it seems probable the mutual influence of one fork on the other is extremely slight. The coupling can be reduced very considerably by working with small deflections, reduced by adding resistance to the galvanometer circuit. A comparison of the beats with various deflections (for the same amplitude) might indicate the magnitude of the coupling effect if observable.

ABSTRACT.

The method consists in putting the windings of the maintaining magnets in series with each other and with a sensitive vibration galvanometer. The beats are clearly shown by the pulsations of the band of light on the scale.

DISCUSSION ON PREVIOUS THREE NOTES.

Mr. D. J. **Blaikley** said that in connection with the harmonics or partial tones there was considerable confusion of terminology. Some writers confine the term *harmonics* to those in arithmetical progression with the fundamental. Partial tones not in this series should simply be called partial tones. For instance, in a tuning fork the first partial tone is not harmonic.

Dr. D. **Owen** thought the vibration galvanometer method for comparing frequency and measuring decrements was much better than any method using a telephone. Why was the method principally applicable to low-frequency forks ? With regard to the tuning fork generator, he could not see on what grounds Mr. Campbell states that he gets a sine-wave current.

Mr. I. **Williams** asked if Mr. Campbell had tried an electromagnet with this apparatus. One could then control the shape of the field, and therefore the wave form of the E.M.F.

Mr. L. **Hopwood** said he would like to thank Mr. Campbell for the helpful remarks with which the demonstration had been accompanied. If he had had that information early in the war it would have saved him a considerable amount of wasted time.

Prof. **Lees** said he was interested in the point about the influence of the measuring apparatus on the results. He thought the effect would be very small. We know the amount by which damping modifies frequency and the damping due to the power taken by the galvanometer was very little In connection with the position of microphones he had once been experimenting with a diaphragm. When tilted so that the concavity due to gravity was upwards, it worked regularly. In other positions it was much less regular.

Mr. **Campbell** said he was interested in Mr. Blaikley's remarks. He was right as to the nomenclature of partial tones and harmonics. Even Lord Rayleigh, he thought, called the tone at 666 the first harmonic of the 100 fork. So did the French writers. In reply to Dr. Owen, he only mentioned low frequencies because the method was the only one suitable for these frequencies. Higher frequencies could easily be done acoustically. With regard to the wave-form obtained with the generator, if one waves a bit of paper rapidly to and fro in front of the galvanometer spot it is clear that the E.M.F. is *nearly* of sine form. This was all he claimed for it at present. With regard to Prof. Lees' observations, he quite realised that the effect of the damping on the frequency of the forks would be very slight, but he was rather thinking of the effect of resonance in pulling the two forks more nearly together. The explanation of the behaviour of the telephone diaphragm mentioned by Prof. Lees might probably throw light on the behaviour of the hummers. He had never known why the tilt was effective.

Prof. **Bickerton**: Why isn't the horizontal position best, then ?

Mr. **Campbell**: Probably in that case the tighter packing of the granules interferes with the efficient working.

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